DISCLAIMER

INCREASED OIL PRODUCTION AND RESERVES UTILIZING SECONDARY/TERTIARY RECOVERY TECHNIQUES ON SMALL RESERVOIRS IN THE PARADOX BASIN, UTAH

Contract No. DE-FC22-95BC14988

Utah Geological Survey (UGS), Salt Lake City, Utah 84114-6100

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Objectives

The primary objective of this project is to enhance domestic petroleum production by demonstration and technology transfer of an advanced oil recovery technology in the Paradox basin, southeastern Utah. If this project can demonstrate technical and economic feasibility, the technique can be applied to about 100 additional small fields in the Paradox basin alone, and result in increased recovery of 150 to 200 million bbl of oil. This project is designed to characterize five shallow-shelf carbonate reservoirs in the Pennsylvanian (Desmoinesian) Paradox Formation and choose the best candidate for a pilot demonstration project for either a waterflood or carbon dioxide-(CO_2-) flood project. The field demonstration, monitoring of field performance, and associated validation activities will take place in the Paradox basin within the Navajo Nation. The results of this project will be transferred to industry and other researchers through a petroleum extension service, creation of digital databases for distribution, technical workshops and seminars, field trips, technical presentations at national and regional professional meetings, and publication in newsletters and various technical or trade journals.

Summary of Technical Progress

Three activities were completed this quarter as part of the geological and reservoir characterization of five productive carbonate buildups in the Desert Creek zone of the Paradox Formation of the Paradox basin, San Juan County, Navajo Nation, Utah (Fig. 1): (1) economic assessments of reservoir CO_2 floods and recommendations, (2) reserve and recovery determinations, and (3) technology transfer.

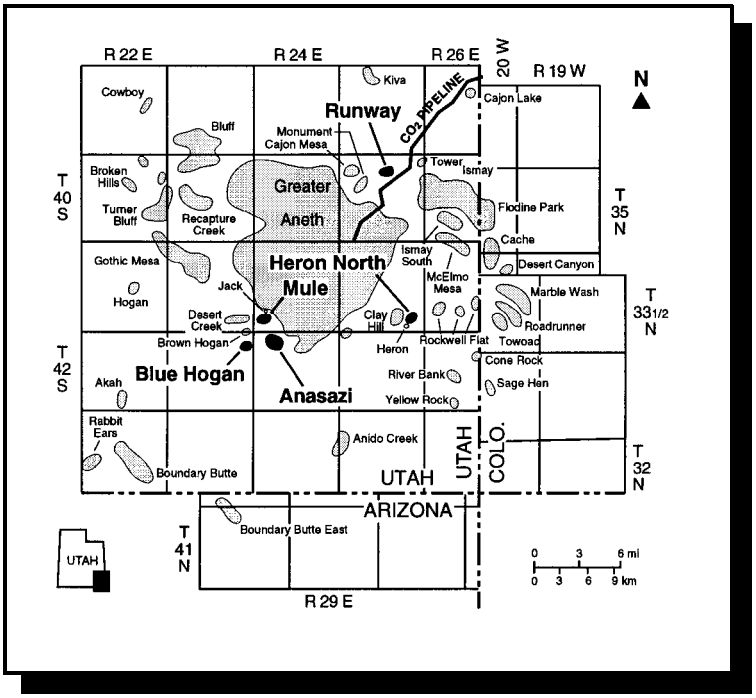


Fig. 1. Location of project fields (dark shaded area with name in bold type) in the southwestern Paradox basin on the Navajo Nation, San Juan Co., Utah.

Economic Assessments of Reservoir CO_2 Floods and Recommendations

Summary

The principal objectives of the study were to develop detailed quantitative descriptions of shallow-shelf carbonate buildups (algal mounds) and use these descriptions coupled with composition simulation to predict the performance of the reservoirs in the mound complexes under three different reservoir recovery processes. The three processes are: primary depletion, CO_2 flooding, and waterflooding.[1] The economic feasibility of implementing one or more recovery processes was also investigated.

Compositional simulation studies were conducted for Anasazi and Runway fields (Fig. 1).[1] The results indicate that CO_2 flooding is the only technically feasible recovery process suitable for these reservoirs. Based on this conclusion, CO_2-flood implementation costs were developed. Implementation costs in conjunction with reservoir performance production and injection predictions were used to complete a suite of economic assessment studies. One of the various CO_2-implementation options studied provided the best economic return; a continuous CO_2-injection case utilizing re-injection of unprocessed produced gas, a leased main injection compressor, and U.S. Department of Energy (DOE) cost share, provided a before-tax net present value (NPV) discounted at 10% per year of more than $5.9 million and before-tax rate of return (ROR) of 32% on a total investment of $2.7 million for Anasazi field. The profitability index (PI) of this particular implementation was determined to be 10.4 to 1.0. For Runway field, before-tax NPV discounted at 10% per year would be more than $3.1 million with a before-tax ROR of 30% on a total investment of $2.79 million. The PI of this particular implementation was determined to be 5.0 to 1.0.

The study results on predicted CO_2 flood responses and the associated economics, support the extension of the overall shallow-shelf carbonate evaluation program to Phase II. Phase II involves the implementation and completion of a CO_2 flood in the Anasazi or Runway reservoirs.

Anasazi Field

Economic assessment of CO_2 flood. Using reservoir simulation based performance predictions and current CO_2-flood implementation costs, detailed economic assessments were conducted for a number of different CO_2-flood options. These sets of studies indicated that:

1. A CO_2 flood of the Anasazi reservoir has robust economics. With DOE participation the project would have a ROR of 62%, a payout of 35 months, a PI of 15 to 1, and a discounted (10%) NPV in excess of $12.5 million. Even without DOE participation the economics remain robust with a ROR of 48%, a payout of 39 months, a PI of 8 to 1, and a discounted NPV of over $11.0 million. The capital requirements would be $3.146 million.

2. Leasing the compressor on a five year contract basis is better economically than purchasing the compressor. Leasing improves the ROR by approximately $1.0 million.

3. The benefit from separating CO_2 from hydrocarbons in produced gas and using the hydrocarbons for fuel and sales are offset by the large capital investment required for a membrane separation facility. Thus, re-injection of all produced gas without processing is economically more attractive than implementing a CO_2 flood with gas processing.

4. The difference between a minimum and maximum cost option for installation of flow/injection lines and the CO_2 supply is approximately $1.0 million; however, the economics are still robust. With DOE cost sharing, the ROR is 56% with a PI of 11.5 to 1.

5. The ROR and PI are not significantly different for a process using blowdown after six years of CO_2 injection versus the continuous CO_2 injection case. However, the NPV is substantially less with blowdown (approximately $1.4 million). The lower NPV is a result of lower oil recovery for the blowdown case (800,000 stock tank barrels [STB] less than the continuous injection case).

Production data and injection gas requirements, including CO_2 make-up purchases, were used to assess, from an economic standpoint, the financial merits of CO_2 flood with a 8.0 million cubic feet of gas per day (MMCFGPD) total injection rate commencing January 1, 2000. The economic assessment, using two compressor options, was conducted assuming the following conditions: (1) leased compressor (option 1 - $19,500/option 2 - $23,500 [same compressor with a different engine]), (2) CO_2 supply line construction using the minimum costs option ($825,000), (3) no gas processing, and (4) cost sharing by DOE. This assessment demonstrates that CO_2 flooding provides

both an adequate flood response with either of the compressor options, an acceptable economic ROR of 32%, and a payout of 36 months. A discounted (10%) NPV of $5.9 million could be realized by implementing a CO_2 flood under the proposed conditions.

In summary, if the CO_2 flood performs as predicted, it is a financially robust process for increasing the reserves of the Anasazi reservoir; however, the ROR and NPV are very sensitive to oil prices (Figs. 2 and 3). Therefore economics should be re-run before installation of injection facilities.

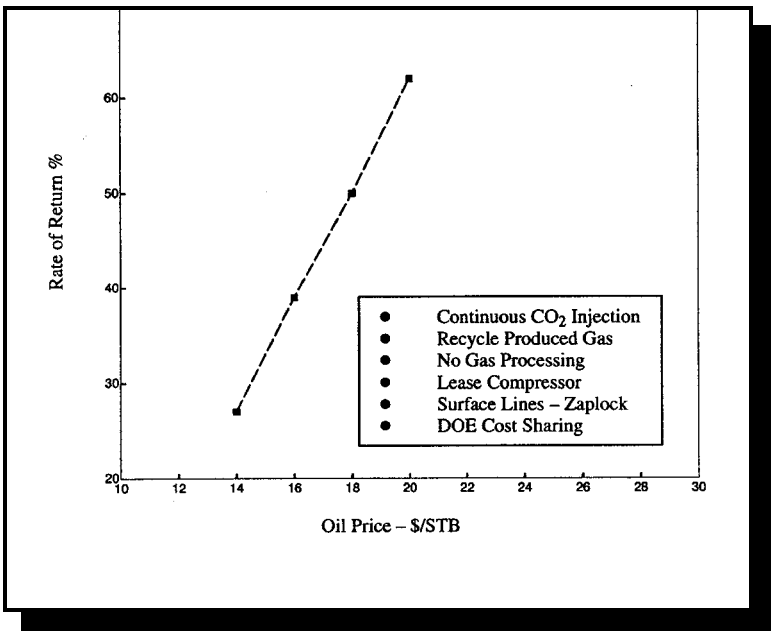
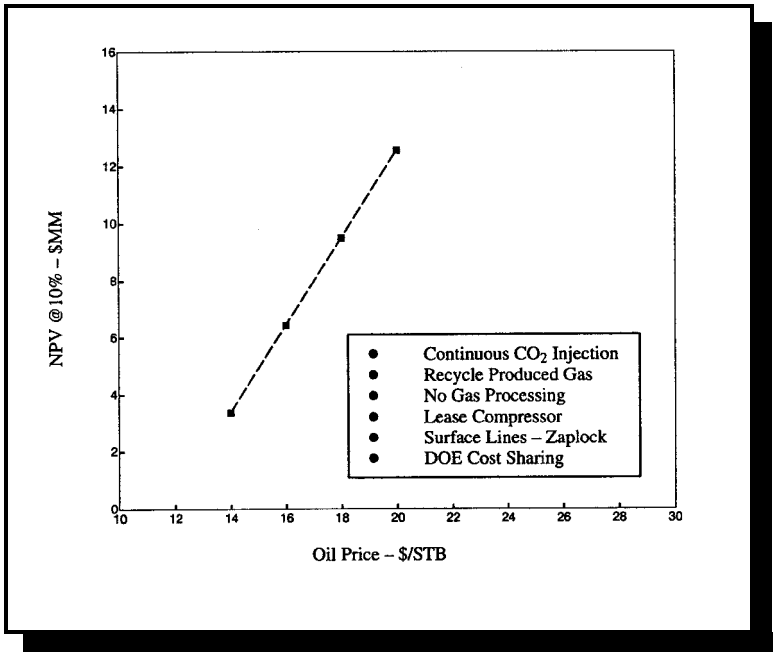


Fig. 2. Rate of return versus price of oil, Anasazi field CO_2 flood at high rate.

Recommendations. Based on the results of the completed geologic study, reservoir performance

Fig. 3. Net present value versus price of oil, Anasazi field CO_2 flood at high rate.



predictions, and the associated economic assessment of implementing a CO_2 flood in the Anasazi reservoir, the following production scenario is recommended.

1. A CO_2-injection project should be implemented in the Anasazi reservoir.

2. A field injectivity test using CO_2 should be conducted on the Anasazi No. 6H-1 well, a project well in the western part of the field, to establish long-term injection rate data before committing to further Phase II work.

3. After the CO_2 source is obtained for Anasazi field, economics should be re-run to see if the project is still economically feasible at current prices.

4. The main injection compressor should be leased rather than purchased to provide the most operating flexibility and least financial risk.

5. Produced gas processing is not required for a single field CO_2-flood implementation case. It is not required from a reservoir processing standpoint nor it is justified economically.

6. Horizontal well injectivity should be predicted from the appropriate well-test models after calibration with vertical well-test data.

Runway Field

Economic assessment of CO_2 flood. Using reservoir simulation-based performance predictions and current CO_2-flood implementation costs, detailed economic assessments were conducted for five different CO_2-flood options. This set of studies indicated that:

1. A CO_2 flood of the Runway reservoir has acceptable economics. With DOE participation the project would have a ROR of 30%, a payout of 32 months, a PI of 5 to 1, and a discounted (10%) NPV in excess of $3.1 million. Even without DOE participation the economics remain acceptable with a ROR of 21%, a payout of 39 months, a PI of 2.8 to 1, and a discounted NPV of almost $2.0 million. The capital requirements would be $2.789 million.

2. Based on the Anasazi study, leasing rather than purchasing a compressor was adopted for the Runway evaluation.

3. The difference between a minimum and maximum cost option for installation of flow/injection lines and the CO_2 supply is approximately $233,000; however, the economics are still acceptable. With DOE cost sharing, the ROR is 29% with a PI of 4.8 to 1, and a discounted NPV of $2.9 milllion.

4. Most economic evaluations exhibited negative cash flows in the year 2008, when operating costs exceed revenues. At this point the projects were terminated. However, the reservoir process should have been changed from continuous CO_2 injection to blowdown and the economics re-run. The additional recovery from blowdown, without the operating costs associated with CO_2 injection, would improve economic returns. Thus, additional prediction runs should be completed to assess the economic effect of conversion to blowdown.

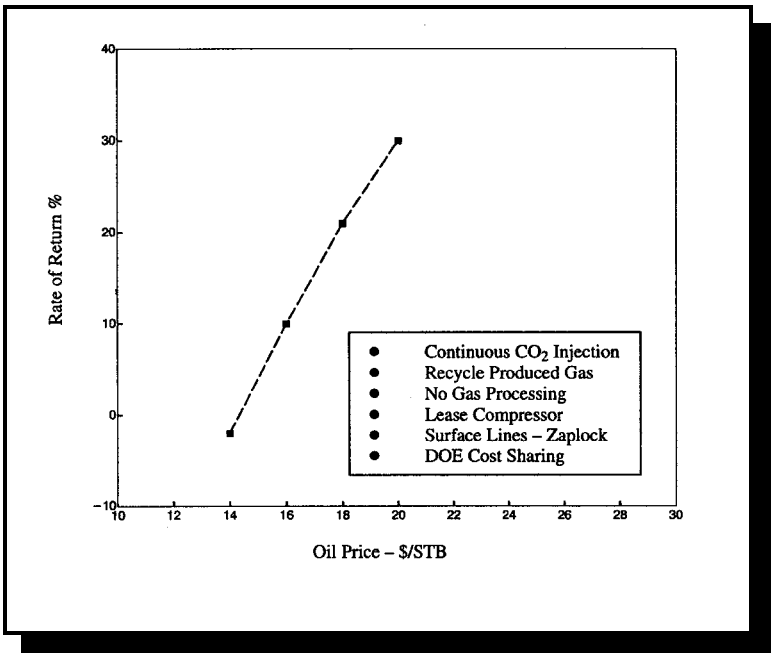


Fig. 4. Rate of return versus price of oil, Runway field CO_2 flood at high rate.

In summary, if the CO_2 flood performs as predicted, it is a financially acceptable process for increasing the reserves of the Runway reservoir. As in Anasazi field, the ROR and NPV are very sensitive to oil prices (Figs. 4 and 5). Therefore economics should also be re-run before installation of injection facilities.

Recommendations. Based on the results of the completed geologic study, reservoir performance predictions, and economic evaluations using a $20/bbl oil price of a CO_2 flood in Runway field, the following production scenario is recommended.

1. A CO_2-injection project could be implemented in the Runway reservoir.

2. A field injectivity test using CO_2 should be conducted on a Runway well to establish long-term injection rate data before committing to further Phase II work.

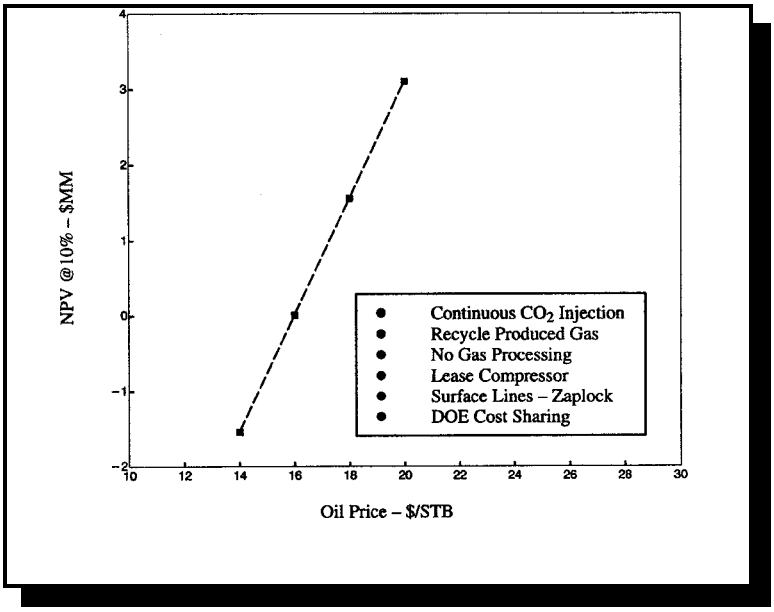


Fig. 5. Net present value versus price of oil, Runway field CO_2 flood at high rate.

3. After the CO_2 source is obtained for Runway field, economics should be re-run to see if the project is still economically feasible at current prices.

4. The main injection compressor should be leased rather than purchased to provide the most operating flexibility and least financial risk.

5. The economic trade off of shutting in producers during reservoir fill-up versus continued production during fill-up should be assessed.

6. Horizontal well injectivity should be predicted from the appropriate well-test models after calibration with vertical well-test data.

Conclusions

Budget Period I of the project showed that a CO_2 flood was technically superior to a waterflood and was economically feasible. For Anasazi field, an optimized CO_2 flood is predicted to recover a total 4.21 million STB of oil. This represents an increase of 1.65 million STB of oil over predicted primary depletion recovery at January 1, 2012. The projected 4.21 million STB of oil production represents in excess of 89% of the original oil in place (OOIP) in the mound complex and 36.8% of the OOIP of the total system modeled. For Runway field, the best CO_2 flood is predicted to recover a total of 2.4 million STB of oil. This represents an increase of 1.58 million STB of oil over predicted primary depletion recovery at January 1, 2012. The projected 2.4 million STB of oil production represents 71% of the OOIP in the mound complex and 48% of the OOIP of the total system modeled, excluding the Ismay zone above the Desert Creek zone.

The Utah Geological Survey (UGS) recommends continuation of the project into Budget Period II with a field demonstration of the technique on the Anasazi or Runway fields. The field demonstration includes: conducting a CO_2 injection test(s), obtaining a CO_2 source and fuel gas for the compressor, rerunning project economics, drilling a development well(s) (vertically or horizontally), purchasing and installing injection facilities, monitoring field performance, and validation and evaluation of the techniques. These activities will take place within the Navajo Nation, San Juan County, Utah.

The demonstration will prove (or disprove) CO_2-flood viability and thus help determine whether the technique can be applied to the other small carbonate buildup reservoirs in the Paradox basin. The financial impact of simultaneous or sequential flooding of a series of reservoirs should also be assessed. This will quantify the upside potential of CO_2 flooding for the entire basin from both a reserves and an economic standpoint. The experience gained in matching historic production and predicting the performance of the Anasazi and Runway reservoirs indicates that the overall mound geometry and internal facies architecture are critical to matching and predicting performance. Thus, each mound will likely require an individual reservoir study to quantify its CO_2-flood potential and identify the appropriate implementation strategy to maximum oil recovery.

Reserve and Recovery Determinations

The cumulative production for the five project fields as of July 1, 1998, is summarized on Table 1. Heron north field is currently shut-in.[2] Primary recovery and OOIP (Table 2) were determined from volumetric reserve calculations, material balance calculations, and decline curve extrapolations as well as refined geologic characterization. These volumetric calculations were made by evaluating well logs and reservoir aerial extent (as defined by seismic) coupled with reservoir geometry. Material balance and decline curve calculations utilized the production and pressure history. Knowing the OOIP and the primary recovery, the amount of oil left behind was calculated. Lastly, utilizing the results from the simulation studies of Anasazi and Runway fields, sweep efficiencies for CO_2 flooding and the ultimate enhanced recovery were estimated for all project fields (Table 2). Using the average predicted oil recovery of 71.8% (percent recovery of remaining oil in place after primary recovery) for the Runway and Anasazi reservoirs, the projected addition to reserves if CO_2 is also applied to project fields is over 8.2 million STB of oil.

TABLE 1.

Cumulative Production from Project Fields

Project Field	Cumulative Production*		
	Oil (bbl)	Gas (MCF)	Water (bbl)
Anasazi	1,855,126	1,581,621	29,335
Blue Hogan	306,468	295,821	1,874
Heron North	206,446	328,713	34,820
Mule	399,887	260,138	29,250
Runway	794,669	2,620,789	5,505

* As of July 1, 1998[1]

TABLE 2

Reserve and Recovery Determinations

Project Field	OOIP* (MSTB)	Primary Recovery		ROIP** (MSTB)	CO_2 Flood Projected Recovery (MSTB)	CO_2 Flood Recovery % ROIP
		Oil (MSTB)	Gas (MCF)			
Anasazi†	4,706	2,000	1,890,000	2,706	2,208	81.6
Blue Hogan	2,530‡	321	968,000	2,209	1,586	71.8
Heron North	2,640‡	216	2,650,000	2,424	1,740	71.8
Mule	2,000‡	454	288,000	1,546	1,110	71.8
Runway	3,372	825	2,830,000	2,547	1,577	61.9

* Original oil in place (thousand stock tank barrels [MSTB]), mound-core and supra-mound intervals (includes platform interval in Runway)
** Remaining oil in place
† High rate case starting CO_2 flood January 1, 2000
‡ Estimate based on approximate volumetric data

Technology Transfer

An article highlighting the successful completion of a project horizontal well in Mule field was published in the UGS news magazine *Survey Notes*.[3] The purpose of *Survey Notes* is to provide nontechnical information on contemporary geologic topics, issues, events, and ongoing UGS projects to Utah's geologic community, educators, state and local officials and other decision makers, and the public. *Survey Notes* is published three times yearly with about 1800 copies distributed.

A paper was prepared for publication by the American Association of Petroleum Geologists (AAPG) describing the facies and reservoir characteristics of the project fields, and the Anasazi field modeling and simulation results.[4] An abstract describing the diagenetic characterization of the reservoirs in the project fields was submitted and accepted for presentation at the 1999 AAPG Annual Convention in San Antonio, Texas.

The project home page on the UGS Internet web site (http://www.ugs.state.ut.us/paradox.htm) was updated with the latest quarterly technical report and project publications list.

References

1. T. C. Chidsey, Jr., and M. L. Allison, Increased Oil Production and Reserves Utilizing Secondary/Tertiary Recovery Techniques on Small Reservoirs in the Paradox Basin, Utah,

Annual Report, DOE Contract No. DE-FC22-95BC14988, DOE/BC/14988-10 (DE98000493), July 1998.

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3. T. C. Chidsey, Jr., *Paradox Basin Project Yields Successful Horizontal Well*: Utah Geological Survey, Survey Notes 31 (1): 3-4 (1998).

4. S. L. Montgomery, T. C. Chidsey, Jr., D. E. Eby, D. M. Lorenz, and W. E. Culham, Pennsylvanian Reserves in Heterogeneous, Shallow-Shelf Reservoirs: *Amer. Assoc. of Petrol. Geol. Bull.* In press.